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COVER SHEET FOR TECHNICAL MEMORANDUM

TITLE- Midcourse Correction Penalties Due to Expected Translunar Injection Deviations

TM- 67-2012-2

DATE- June 14, 1967

FILING CASE NO(S)- 310

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FILING SUBJECT(S)-
(ASSIGNED BY AUTHOR(S)- Translunar Midcourse Correction

(NASA-CR-67087) MIDCOURSE CORRECTION PENALTIES DUE TO EXPECTED TRANSLUNAR INJECTION DEVIATIONS (Bellcomm, Inc.) 26 p

N79-71987

Unclas
00/13 12921

ABSTRACT

A study has been conducted to ascertain the effects of various factors on the Translunar Midcourse correction penalties for an Apollo Lunar Mission. The factors studied included, Launch Site position uncertainties, off-nominal performance of the propulsion and sensing systems during the Earth Launch and the Translunar Injection phases, and off-nominal venting during Earth Parking Orbit. In addition, several different state vector update techniques during Earth Parking Orbit were investigated.

It was shown that off-nominal venting makes a significant contribution to the midcourse ΔV penalty when there is no state vector update during Earth Parking Orbit. With a reasonable update method, however, the contribution of venting effects is negligible. It was also shown that, for the trajectory studied, a state vector update in Earth Parking Orbit resulted in approximately a 30% decrease in the midcourse ΔV penalty.

It was demonstrated that combining the tracking data from one station with the onboard estimated state vector can result in midcourse ΔV penalties near that obtained with an error free update.

It was shown that the dominant contributors (from powered flight maneuvers) to the midcourse ΔV penalty consisted of gyro and accelerometer error sources located in the plane of flight and TLI engine cutoff time uncertainty.

[redacted] (ACCESSION NUMBER)	(THRU)
26 (PAGES)	2C (CODE)
CR-87087 (NASA CR OR TMX OR AD NUMBER)	30 (CATEGORY)

FACILITY FORM 602

BA-145A (3-67)

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SUBJECT: Midcourse Correction Penalties Due to Expected Translunar Injection Deviations - Case 310

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FROM: D. A. Corey
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TECHNICAL MEMORANDUM

1.0 INTRODUCTION

This memorandum reports the results of a study of the effects of various factors on the Translunar Midcourse correction penalties for an Apollo Lunar mission. The factors studied were:

1. Launch site position uncertainties

2. Off-nominal performance of the launch vehicle propulsion and sensing systems during the Earth launch to Earth Parking Orbit Insertion phase

3. Off-nominal venting in Earth Parking Orbit

4. Various methods of state vector updating prior to Translunar Injection

5. Off-nominal performance of the S-IVB propulsion and sensing systems during the Translunar Injection phase.

The study included two effects which have not previously been considered . These were:

1. The correlation between actual errors and the uncertainties in the errors at Earth Parking Orbit Insertion.

2. The error correlations resulting from the use of the same inertial reference equipment in the Earth Launch and the Translunar Injection powered flight phases.

[redacted]

Two sources of midcourse correction penalties were not considered in the study. They are:

1. Navigation errors in the Translunar coasting phase, and

2. Performance errors during the midcourse correction burns.

The end results of the study are the midcourse ΔV penalties caused by each of the various effects, considered both collectively, and individually.

The study was performed utilizing linear perturbation techniques about one reference trajectory whose general characteristics are summarized as follows:

1. Earth Parking Orbit stay-time of approximately two orbits,

2. Translunar flight in the Earth-Moon plane,

3. Translunar flight time of approximately 59.7 hours.

This trajectory is defined in more detail as trajectory No. 1 in the Bellcomm document listed as Reference 1.

2.0 GENERAL DISCUSSION AND ASSUMPTIONS

2.1 Computer Programs Used

The study utilized two computer programs developed for the purpose of the study. The first program, known as the Statistical Error Analysis Program (SEAP) was designed to manipulate large covariance matrices and consequently allows propagation of the covariance matrices of state vector errors through both powered and coasting flight mission phases. It includes provisions for incorporating state vector updates in a statistical sense, determining the effects of off-nominal venting, determining midcourse corrections required, and for detailed statistical analysis of covariance matrices. The latter function is used to analyze the covariance matrices of midcourse corrections required and produce single variate descriptions of the covariance matrices in term of the magnitude of the corrections for various values of probability. A detailed description of SEAP is provided in Reference 2.

The second program, known as the Parametric Error Analysis Program (PEAP) was designed to isolate the contributions of individual independent error sources to the midcourse ΔV

penalties. PEAP determines the ΔV penalty due to an error source present in the Earth Launch phase only, the Translunar Injection phase only, and the penalty due to an error source present in both phases. A detailed discussion of PEAP is provided in Reference 3.

Both of the above programs require a considerable volume of input data. The sources and/or the methods of generating this data together with other assumptions of the study are discussed in subsequent paragraphs of Section 2.0.

2.2 Powered Flight Transition Matrices

A set of linerized transition matrices, about the reference trajectory, was generated for both the Earth Launch and the Translunar Injection powered flight phases. These transition matrices relate the actual (real world) errors and the uncertainties in the errors which are present at a predetermined time after a maneuver to actual errors and uncertainties which were present before the maneuver and to vehicle performance and sensing errors which occurred during the maneuver. These matrices were generated using the Bellcomm Powered Flight Performance Simulator (discussed in Reference 4). These transition matrices are based on guided reference trajectories.

The IGM guidance equations used for the TLI maneuver are those associated with the Hypersurface 1 Equations as defined in Reference 5. The guidance equations used for the Earth Launch to Earth Parking Orbit Insertion Maneuver are from the AS-501 LVDC guidance equation defining document, Reference 6.

A comparison of the Earth Parking Orbit Insertion (EPOI) uncertainty covariance matrix was made with the results published by MSFC for the AS-501 mission (Reference 7.) It was found that the results were in reasonable agreement.

2.3 Coasting Flight Transition Matrices

The coasting flight transition matrices, which relate errors at a specified time to errors which existed at a previous time, were generated using the Bellcomm Apollo Simulation Program (BCMASP) (Reference 8). The transition matrices were developed by first establishing the integrated trajectory connecting two principal events, and then perturbing each component of the initial state vector. These perturbed initial state vectors were then integrated to the reference time of the second event. The differences from the reference state vector at the second event were determined and then normalized. A test was made to insure that only the linear terms were included in the transition matrices.

2.4 Navigation Updates

Several methods of updating the state vector during Earth Parking Orbit were studied. These were:

1. No navigation update at all,

2. a perfect stage vector update,

3. an update using tracking information from a single ground station with a two minute tracking arc,

4. an update using tracking information from a single ground station with a four minute tracking arc,

5. an update using tracking information from two ground stations using their entire tracking arcs,

6. an update using combining the tracking information in cases 3, 4, 5, and 6 above, with the on-board a priori estimate of the state vector.

In order to allow time to prepare the space vehicle for the TLI maneuver, it was assumed that the navigation update would occur forty-five minutes prior to nominal TLI engine ignition. The tracking stations used were the last one, two, or eight stations which had visibility at least forty-five minutes before TLI ignition. On the reference trajectory considered, the last station with visbility was Ascension.

The tracking covariance matrices used were generated using the Bellcomm Tracking Analysis Program (BCMTAP) (Reference 9). The input data used to represent the radar error model and sampling rates were extracted from the ANWG document (Reference 10). The tracking data was generated without the effects of off nominal venting in Earth Parking Orbit. Consequently, the tracking data used was better than that which would exist during an actual mission and the resulting midcourse correction penalties are smaller. The effects of off-nominal venting on tracking accuracy is being studied.

The portions of the study concerned with isolations the effects of individual hardware error sources considered only the no update and perfect update cases.

2.5 Off-Nominal Venting Model

The venting model simulated assumed that the off-nominal thrust was perpendicular to the present position vector of the vehicle and in the present orbital plane. The standard deviation of this off-nominal vent was assumed to be a one pound constant thrust.

2.6 Inertial Platform Hardware Performance Characteristics

The MSFC inertial platform hardware error coefficients used in this study to model performance errors are given in Reference 11. The error coefficients defined in Reference 11 differ from those used in MSFC in Reference 7 (i.e., Guidance Error Analysis for Saturn V, AS-501) in the terms associated with initial platform misalignments and for accelerometer misalignments. The remaining terms, those associated with gyro and accelerometer performance, are the same.

2.7 Vehicle Propulsion System Performance Characteristics

The launch vehicle propulsion system performance characteristics and their one sigma values considered during the EOPI and TLI maneuvers are as follows:

1. SIC stage
   a) 0.235 percent thrust deviation with a nominal I_{sp}.
   b) 0.141 percent I_{sp} deviation with a nominal thrust.
   c) a non-nominal propellant loading of 560 slugs.
2. S-II stage
   a) 0.45 percent thrust deviation with a nominal I_{sp}.
   b) 0.141 percent I_{sp} deviation with a nominal thrust.
   c) a non-nominal propellant loading of 72 slugs.
3. S-IVB stage (first and second ignitions)
   a) 1.0 percent thrust deviation with a nominal I_{sp}.
   b) .333 percent I_{sp} deviation with a nominal thrust.

c) a non-nominal mass of 37 and 88 slugs, respectively.

d) a timing error of 0.01 seconds for the second S-IVB ignition.

e) a timing error of 0.01414 seconds for the TLI engine shutdown.

The correlation of these parameters between EPOI and TLI was not considered.

Even though the propulsion system errors are major contributors to the state vector deviations at EOPI and TLI, it will be shown in Section 3.5 that those errors are only very minor contributors to the midcourse (with the exception of the engine shutdown timing error at TLI) correction ΔV requirements. The propulsion system error sources lead to sensed deviations and the guidance system is able to compensate for them during the burn. This leads to correlations in the deviations such that the midcourse penalties are small. For this reason, a complete modeling of error sources associated with the propulsion system was not made.

2.8 Launch Site Position Uncertainties Modeled

The launch site position uncertaintites included in this investigation were 20 feet (1σ) in the vertical direction, 200 feet (1σ) in both the out-of-the desired Earth orbital plane and in the downrange direction. These uncertainties were considered to be statistically uncorrelated at the launch pad.

2.9 Midcourse Correction Criteria

The first midcourse correction was made at five hours past nominal TLI and was designed to achieve the reference trajectory perilune position vector at the time of reference trajectory perilune.

The second midcourse correction was made at the time of the reference trajectory perilune and was designed to null the velocity errors existing at that point.

Perfect translunar navigation was assumed and no execution errors were modeled for the midcourse maneuvers. Consequently, the position errors at the second correction point were zero.

The second correction should not, of course, be considered a separate maneuver at all. Rather, it simply provides a measure of the velocity errors existing at perilune. The excess ΔV required during the Lunar Orbit Insertion maneuver to compensate for the errors is somewhat smaller than the "corrections" calculated. This is especially true because the dominant velocity errors at perilune are in the out-of-plane direction - i.e. azimuth errors at perilune.

Such errors cost very little when combined in a root sum square sense with the large in plane ΔV required in the LOI maneuver.

3.0 DISCUSSION OF STATISTICAL RESULTS

Table 1 presents the pertinent data about the statistics of the midcourse ΔV's which were required for each of the SEAP runs made. The data in Table 1 represent the 99.73% points of the distributions of the magnitude of the required first and second midcourse corrections. Note that the numbers presented in Table 1 represent the statistics of the midcourse ΔV required to correct for actual deviations from the nominal Translunar Injection.

For purposes of brevity, a specific form of notation will be used in this section when discussing the values of the midcourse corrections. They are expressed as the magnitudes of the first midcourse correction followed by the magnitude of the second and separated by a slash, e.g., 20.0/5.0 fps.

It is possible to break up the midcourse correction magnitudes into magnitudes due to several factors. The set of factors considered in this memorandum are:

- $\ddagger_{aa}$ - the covariance matrix of actual deviations at Earth Parking Orbit Insertion
- $\ddagger_{uu}$ - the covariance matrix of uncertainties in the deviations at Earth Parking Orbit Insertion
- $\ddagger_{TLI}$ - the performance errors in the Translunar Injection maneuver
- $\ddagger_{au}$ - the matrix expressing the correlation between $\ddagger_{aa}$ and $\ddagger_{uu}$ at EPOI
- $\ddagger_{ap}$ - the matrix expressing the correlation between the performance errors in TLI and the actual deviations at EPOI
- $\ddagger_{up}$ - the matrix expressing the correlation between performance errors in TLI and the uncertainties in the deviations at EPOI
- Venting - the effects of off-nominal $L\bar{H}_2$ venting in Earth Parking Orbit

Navigation - the effects of the Earth Parking Orbit Navigation update technique.

It was noted that these various factors (excluding navigation) are relatively independent of each other and the contributions due to each may be combined in a root sum square sense to produce the combined effects of the contributors. The contributions of ‡uu, ‡au, ‡up, ‡ap and venting are dependent on the type of navigation update employed however.

Table 2 presents a list of the SEAP runs and indicates which of the above factors were contributors to the results for that run.

The contributions of these factors and the combined results are discussed in the following subsections.

3.1 Basic Results

With no navigation update the required midcourse correction considering all factors was 31.76/4.10 fps (run 2). With a perfect update 45 minutes prior to TLI, the required correction was 21.22/4.31 fps (run 4). These numbers essentially establish the bounds in terms of making a decision as to whether an update is desirable. Certainly any update scheme which results in midcourse corrections larger than the no update case would be unacceptable.

3.2 Effects of Update Schemes

When data obtained from 2 minutes of tracking by a single station was used to update the vehicle state vector, the required midcourse correction increased to 56.71/15.69 fps (run 6). This is considerably higher than the midcourse required in the no update case. When the same tracking data is combined in an optimum fashion with a priori data to provide the update, the resultant midcourse requirement was 22.46/4.46 fps (run 8).

This is very nearly as good as the perfect update case. Thus, the two minute tracking arc is adequate if the data is optimally combined with a priori data but the tracking data alone should not be used.

When the single station tracking arc is increased to four minutes, the required midcourse was decreased to 31.58/15.57 fps using tracking data alone (run 13). This is almost equivalent to the no update case (run 2) except that the 2nd correction is up considerably. Using tracking data only from two stations and 8 stations resulted in midcourse ΔV's of 25.60/4.45 fps and 21.30/4.32 fps, respectively (runs 15 and 17). Combining the tracking data in these cases with a priori data resulted in midcourse requirements which were virtually identical to the perfect update case. With two stations or eight stations, the tracking data alone is adequate.

One very interesting point which is brought out by a comparison of the results from runs 17 and 18 (8 stations, tracking data update and optimum update, respectively) is that here is a case where an optimal update in Earth Parking Orbit cost more midcourse ΔV than did a tracking data only update. The identical tracking covariance matrix was used in both runs. The criteria for optimality of an optimal update is that the sum of the eigenvalues of the resultant covariance matrix be minimized. This means that the uncertainty, at the update point, is minimized. It does not mean that any other cost function is necessarily minimized. In this particular case, after the optimal update, the remaining correlations between the uncertainties and actual deviations and between the uncertainties and the peformance parameters was such that the midcourse correction cost (or penalty) was slightly greater than when using just the tracking data alone for the update. This was an interesting, though not too dramatic result. It does serve to point out that care should be taken to define in what sense a system is optimal.

3.3 Effects of Venting

With no tracking update the venting uncertainty contributed about 19.21/1.79 fps (runs 1 and 2). With a perfect update, the off-nominal venting contribution was about 2.20/.34 fps (runs 3 and 4). In the perfect update case, only 45 minutes of venting is included in the uncertainties at the beginning of TLI, whereas almost 3 hours of venting uncertainty is present in the no update case. The actual deviations are affected equally in both cases, but as will be discussed in subsection 3.5, the actuals have little effect. The venting contribution varied between these two extremes for the other update methods.

3.4 Effects of Powered Flight Maneuvers

The individual contribution of the EOPI maneuver is seen in the results of run 12 which involved no TLI performance errors, no update and no venting. The midcourse penalty due to

EPOI performance errors alone was 26.19/2.11 fps. The contribution of the TLI performance errors is seen in run 9 which involved a perfect EOPI maneuver and no venting. The midcourse penalty due to TLI alone was 21.09/3.88 fps. These figures are trajectory dependent since the dominant errors are caused by hardware performance charactristics which in turn are dependent on the time spent in Earth Parking Orbit and by platform orientation during the TLI maneuver. This area will be discussed further in Section 4.0.

3.5 Effects of Actuals vs. Uncertainties at EPOI

The effects of $\ddagger_{aa}$ are isolated in run 10 and are seen to be .263/1.36 fps. The effects of $\ddagger_{uu}$ are isolated in run 11 and are 26.29/2.41 fps. $\ddagger_{uu}$ is seen to be the major contributor to the midcourse penalty whereas $\ddagger_{aa}$ is a very minor contributor. The TLI maneuver essentially removes any known errors but can do nothing to correct for the uncertainties. This result demonstrates the fact that if deviations are sensed before the TLI maneuver, the guidance system compensates for them extremely well. The removal of these known deviations does result in a fuel penalty for the S-IVB during the TLI maneuver. It is interesting to note that the RSS combined effects of $\ddagger_{aa}$ and $\ddagger_{uu}$ does not equal the midcourse penalty due to all EPOI effects (Section 3.4). This is caused by $\ddagger_{au}$, the correlation between $\ddagger_{aa}$ and $\ddagger_{uu}$ and is discussed in Section 3.6.

The effects of the $\ddagger_{uu}$ factor are known to be trajectory sensitive to some extent, since its propagation is dependent on the time spent in Earth Parking Orbit.

3.6 Effects of Correlation

The effect of $\ddagger_{au}$, the matrix which expresses the correlation between $\ddagger_{aa}$ and $\ddagger_{uu}$ at EPOI was most interesting. The values associated with this factor may be derived from runs 10, 11 and 12. The contribution of $\ddagger_{au}$ is -2.46/-2.06 fps, where the minus sign refers to the fact that the square of the magnitude bears a minus sign when combining this contribution with others in a root sum square sense. Accounting for the correlation between $\ddagger_{aa}$ and $\ddagger_{uu}$ decreases both the first midcourse and the second midcourse requirements due to $\ddagger_{aa}$ and $\ddagger_{uu}$. The contribution of $\ddagger_{au}$ is, to some extent, trajectory dependent, and will be the subject of further investigation.

The contribution of $\ddagger_{ap}$, the correlation between performance errors in TLI and actual deviations prior to TLI, was 2.72/3.08 fps. The values associated with this factor were derived from runs 3, 9 and 10.

The contribution of $\ddagger_{up}$, the correlation between the performance errors in TLI and the state vector uncertainties prior to TLI, was -22.26/-3.29 fps. The values associated with this factor were derived from runs 1, 3, 10 and 12.

The correlations exist because the same inertial platform is used for both the EOPI and the TLI maneuvers. Subsequent studies are expected to demonstrate the contributions of $\ddagger_{au}$, $\ddagger_{ap}$ and $\ddagger_{up}$ are highly trajectory dependent. The trajectory studied placed the TLI maneuver very nearly over the Earth launch site. Separating the maneuvers by 90 or 180 degrees is expected to change the $\ddagger_{au}$, $\ddagger_{ap}$ and $\ddagger_{up}$ contributions significantly.

The net contribution of these correlation terms is -21.64/-2.94 fps indicating that they cancel out much of the effects of the entire EPOI maneuver for this reference trajectory.

3.7 Effects of Launch Site Position Uncertainties

The effects of the launch site position uncertainties were isolated. These effects were included in the previous discussion of EPOI effects and can be looked at as just a subset of the total contributors to the $\ddagger_{uu}$ effects (run 11). The net contribution of the launch site position uncertainties (as defined in section 2.8) was 3.60/.284 fps. This is a surprisingly large midcourse penalty for such relatively small uncertainties at the launch pad, and indicates that they should not be neglected in error analysis studies.

4.0 DISCUSSION OF INDIVIDUAL ERROR SOURCE RESULTS

Table 3 contains a list of the hardware and propulsion system error sources that were modeled. Table 4 presents the pertinent data about the statistics of the midcourse ΔV's which were required for each error source. These numbers represent the 1σ(68.269%) points of the individual error source distributions for both the first and second midcourse corrections. The notation used (e.g., 20.0/5.0 fps) is that defined in Section 3.0.

Table 4 contains data from five different cases. These cases are as follows:

1. EPOI actual deviations and uncertainties only, with a perferct navigational update in Earth Parking Orbit prior to a perfect TLI.

2. EPOI actual deviations and uncertainties only, with no navigational update in Earth Parking Orbit and with a perfect TLI.

3. TLI errors only. The actual deviations and uncertainties prior to TLI were zero.

4. EPOI actual deviations and uncertainties, with a perfect navigational update in Earth Parking Orbit prior to a non-perfect TLI.

5. EPOI actual deviations and uncertainties, with no navigational update in Earth Parking Orbit and with a non-perfect TLI.

The hardware performance error results are given in the standard coordinate system 13 for Launch Vehicle Navigation as given in Reference 12.

The error sources which dominate the midcourse ΔV penalty have been selected from Table 4 and form the contents of Table 5. The basis of selection was that an error source required greater than .5 fps (1σ) for the first midcourse correction. Table 5 indicates that 13 of the 44 error sources modeled, played a dominant role in the midcourse ΔV penalty. The 13 error sources considered dominant are the 12 in the 5th column of Table 5 plus GCDX (the X gyro constant drift term) which is present in the second, third and fourth columns but not in the fifth column.

4.1 Dominant Initial Misalignment Effects

The only dominant initial misalignment error was INMISY which is an initial vehicle pitch error. This error source resulted in a 1σ midcourse penalty of 1.275/.090 fps for the EPOI & TLI with no update case. This midcourse ΔV penalty was almost solely due to performance during the EOPI maneuver, so that varying the Earth Parking Orbit (EPO) stay time or having a reasonable update during EPO would materially effect these results.

4.2 Dominant Gyro Error Source Effects

The dominant gyro error sources were the constant drift rate of each of the three gyros (GCDX, GCDY, and GCDZ) plus the gyro errors sensitive to in plane acceleration, (the X-Z plane of the platform). These acceleration dependent drift rate error sources are GMUX, GDSAY, GEPTX, GEPTY.

As can be seen from the results in Table 4, the constant gyro drift effects were appreciable for both the EPOI and TLI maneuvers as well as when they were combined. This means that these effects would not be necessarily reduced by an update in EPO (see column 4 of Table 4). In addition, these effects are highly EPO stay time dependent.

The midcourse ΔV penalties associated with the acceleration dependent drift rate terms was almost solely due to performance during the EPOI maneuver, so that varying the EPO stay time or having a reasonable update during EPO would materially effect these results.

4.3 Dominant Accelerometer Error Source Effects

The dominant accelerometer error sources were the alignment error of the X accelerometer in the X-Z plane (AMSXXX), alignment error of the Z accelerometer in the X-Z plane (AMSZXZ), constant bias of the Z accelerometer, and the scale factor error of the Z accelerometer.

As can be seen by reviewing the results in Table 4 for these error sources, the errors incurred during the EPOI maneuver for these error sources contributed to the majority of the midcourse ΔV penalties. Therefore, these results are EPO stay time dependent and a reasonable update during EPO would tend to materially reduce the midcourse ΔV penalty.

4.4 Dominant Timing Error Effects

The dominant timing error effect was caused by an error in TLI cutoff time (TIMCOU). This error source includes the effects of thrust tail off uncertainty plus scheme error in determining the correct cutoff time. The midcourse ΔV penalty for a 14.14 millisecond timing error was 3.026/.094 fps. This error source is strictly independent of EPO stay time or update. The high sensitivity of this error source to midcourse ΔV places it in the category of special concern.

4.5 Dominant Propulsion and Mass Perturbation Effects

There were no error sources in this category which lead to significant midcourse ΔV penalties. These error sources lead to sensed deviations during a powered flight maneuver and are effectively guided out (see Section 3.5).

5.0 CONCLUSION

The study had demonstrated that for the trajectory studied and with no state vector update, the 3 sigma magnitudes of the required midcourse corrections are 31.76 fps and 4.10 fps for the first and second midcourses, respectively. These figures do not include the effects of translunar flight navigation errors, or midcourse correction performance errors. If a perfect state vector update is made 45 minutes prior to Translunar Injection, the midcourse penalties are reduced to 21.22 fps and 4.31 fps, respectively. Updating the state vector using only data from a single station tracking for two minutes is worse than no update at all. Combining this tracking data optimally with a priori data reduces the midcourse penalties to slightly more than the perfect update values. Updating the state vector with tracking data only from a single station tracking for four minutes reduces the first midcourse penalty to be slightly better than the no update case but the second midcourse penalty was substantially increased. Updating with only tracking data from two or more stations yields results near the perfect update case.

Venting uncertainty caused significant increases in the midcourse penalties when no update is made (19.21 and 1.79 fps). With an update, the contribution of the venting uncertainty is negligible.

The uncertainties which exist at Earth Parking Orbit Insertion were shown to be the major contributors to the midcourse penalties when no update is made. The launch site position uncertainties were shown to be a significant contributor to this midcourse ΔV penalty. If deviations are known, the TLI maneuver compensates for them and the resulting midcourse penalties due to EPOI dispersions are quite small.

The effects of correlations between the various errors were shown to be significant with no update. With an update using reasonable tracking date, the only significant contributor to the midcourse requirements was the performance errors in the TLI maneuver which amounted to 21.09 and 3.88 fps for the two midcourses, respectively.

The contributions of the individual error sources to the midcourse ΔV penalty were studied. It was found that a minority of the error sources (13 out of the 44 considered) cause almost all of the ΔV penalty. Generally, these major error sources consisted of gyro and accelerometer errors located in the plane of flight and TLI engine cutoff time uncertainty. The dominant sources are tabulated in Table 5. The high sensitivity of the TLI engine cutoff time uncertainty to midcourse ΔV places it in a category of special concern.

The numerical values expressed are somewhat trajectory dependent but are considered fairly typical of possible Apollo LOR missions. The basic conclusions regarding updates, significance of contributing factors, etc., are not trajectory dependent.

6.0 ACKNOWLEDGEMENTS

The authors are deeply indebted to a number of people who gave their full cooperation in the modification and operation of the various computer programs used in the development of the data for this study. These people were: Miss M. V. Bullock (BCMTAP); M. G. Kelly (BCMASP); D. J. Roek (BCMPEPS); and R. D. Weiksner (SEAP and PEAP).

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Attachments
References
Tables 1 thru 5

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TABLE 1

STATISTICS OF MIDCOURSE CORRECTION ΔV's (SEAP RESULTS)

RUN NO.	TYPE OF UPDATE	SPECIAL REMARKS	OFF-NOMINAL VENTING IN EPO	99.73% OF MAGNITUDE OF 1st MCC(fps)	99.73% OF MAGNITUDE OF 2nd MCC(fps)
1	None		No	25.29	3.78
2	None		Yes	31.76	4.10
3	Perfect		No	21.12	4.31
4	Perfect		Yes	21.22	4.31
5	Tracking Data Only	One Station - 2 minute Tracking Arc	No	56.66	15.69
6	Tracking Data Only	One Station - 2 minute Tracking Arc	Yes	56.71	15.69
7	Optimum	One Station - 2 minute Tracking Arc	No	21.42	4.43
8	Optimum	One Station - 2 minute Tracking Arc	Yes	22.46	4.46
9	None	TLI Errors Only	No	21.09	3.88
10	None	EPOI Actual Errors Only ($\ddagger_{aa}$)	No	.263	1.36

RUN NO.	TYPE OF UPDATE	SPECIAL REMARKS	OFF-NOMINAL VENTING IN EPO	99.73% OF MAGNITUDE OF 1st MCC(fps)	99.73% OF MAGNITUDE OF 2nd MCC(fps)
11	None	EPOI Uncertainties Only (Φ_{uu})	No	26.29	2.41
12	None	EPOI Actuals, Uncertainties and their Correlation. No TLI Errors	No	26.19	2.11
13	Tracking Data Only	One Station - 4 minute Tracking Arcs	Yes	31.58	15.57
14	Optimum	One Station - 4 minute Tracking Arcs	Yes	22.42	4.46
15	Tracking Data Only	Two Stations - Full Tracking Arcs	Yes	25.60	4.45
16	Optimum	Two Stations - Full Tracking Arcs	Yes	21.93	4.38
17	Tracking Data Only	Eight Stations - Full Tracking Arcs	Yes	21.30	4.32
18	Optimum	Eight Stations - Full Tracking Arcs	Yes	21.51	4.33

TABLE 2

PRESENCE OF VARIOUS FACTORS IN THE RUNS

RUN NO.	ACTUAL DEVIATIONS AT TLI - DUE TO EPOI	UNCERTAINTIES AT TLI - DUE TO EPOI	TLI PERFORMANCE ERRORS	CORRELATION BETWEEN ACTUALS AND UNCERTAINTIES AT TLI	CORRELATION BETWEEN ACTUALS AND PERFORMANCE ERRORS AT TLI	CORRELATION BETWEEN UNCERTAINTIES AND PERFORMANCE ERRORS AT TLI	VENTING
1	X	X	X	X	X	X	
2	X	X	X	X	X	X	X
3	X		X		X		
4	X		X		X		~~X~~
5	X	~~X~~	X		X		
6	X	~~X~~	X		X		~~X~~
7	X	~~X~~	X	~~X~~	X	~~X~~	
8	X	~~X~~	X	~~X~~	X	~~X~~	~~X~~
9			X				
10	X						
11		X					
12	X	X		X			
13	X	~~X~~	X		X		~~X~~
14	X	~~X~~	X	~~X~~	X	~~X~~	~~X~~
15	X	~~X~~	X		X		~~X~~
16	X	~~X~~	X	~~X~~	X	~~X~~	~~X~~
17	X	~~X~~	X		X		~~X~~
18	X	~~X~~	X	~~X~~	X	~~X~~	~~X~~

X refers to the presence of the error

~~X~~ refers to an error altered by a state vector update (not zeroed)

TABLE 3

HARDWARE AND PROPULSION SYSTEM ERROR SOURCES INCLUDED IN MODEL FOR THIS STUDY

No.	Symbol	Description
1.	GMUX	Gyro Acceleration dependent Drift Rate caused by acceleration along the input axis.
2.	GMUY	
3.	GMUZ	
4.	INMISX	Platform initial misalignment.
5.	INMISY	
6.	INMISZ	
7.	ASFX	Accelerometer Scale Factor Error
8.	ASFY	
9.	ASFZ	
10.	ACLINX	Accelerometer Linearity Error
11.	ACLINY	
12.	ACLINZ	
13.	AMSXXY	Accelerometer Misalignment Error (example, AMSXXY - X accelerometer misalignment in the X-Y plane)
14.	AMSXXZ	
15.	AMSYXY	
16.	AMSYYZ	
17.	AMXZXZ	
18.	AMSZYZ	
19.	GDSAX	Gyro Acceleration dependent Drift Rate caused by acceleration along the Spin Reference Axis
20.	GDSAY	
21.	GDSAZ	
22.	GCDX	Constant gyro drift
23.	GCDY	
24.	GCDZ	
25.	GEPTX	Gyro Acceleration dependent drift rate caused by acceleration along the output axis. (Gyro End Play Torque)
26.	GEPTY	
27.	GEPTZ	
28.	ACBIAX	Accelerometer Constant Bias Error.
29.	ACBIAY	
30.	ACBIAZ	

Table 3 (cont'd)

31.	TIMIGU	Engine ignition time uncertainty
32.	TIMCOU	Engine cutoff time uncertainty
33.	FTD	Engine thrust deviation during TLI
34.	ISP	Engine Specific Impulse deviation during TLI
35.	MASSD	Vehicle Mass deviation at the start of TLI
36. 37. 38.	MASD-1 MASD-2 MASD-3	SIC, SII, and S-IVB mass deviations during EPOI
39. 40. 41.	FTD-1 FTD-2 FTD-3	SIC, SII, and S-IVB engine thrust deviations during TLI
42. 43. 44.	ISPD-1 ISPD-2 ISPD-3	SIC, SII, and S-IVB engine specific impulse deviations during EPOI

TABLE 4

HARDWARE AND PROPULSION SYSTEM ERROR SOURCE

MIDCOURSE ΔV PENALTIES (1σ)

ERROR SOURCE NAME	EPOI ONLY PERFECT UPDATE	EPOI ONLY NO UPDATE	TLI ONLY	EPOI & TLI PERFECT UPDATE	EPOI & TLI NO UPDATE
1. GMUX	.024/.157	.629/.063	.007/.015	.022/.172	.624/.054
2. GMUY	---/---	.0049/.0004	.032/.0009	.032/.0009	.036/.001
3. GMUZ	.0071/.048	.050/.012	.046/.060	.048/.012	.079/.072
4. INMISX	.023/.164	.121/.0235	.013/.019	.024/.183	.110/.005
5. INMISY	.0060/.007	1.32/.097	.055/.008	.07/.009	1.275/.090
6. INMISZ	.0049/.032	.026/.0087	.003/.004	.007/.028	.029/.013
7. ASFX	.0023/.003	.279/.035	.147/.004	.144/.003	.399/.035
8. ASFY	---/---	---/---	.023/.0007	.023/.0007	.024/.0007
9. ASFZ	.014/.017	2.55/.228	.338/.013	.324/.019	2.871/.239
10. ACLINX	.0002/.0003	.018/.0025	.017/.0005	.016/.0005	.033/.003
11. ACLINY	---/---	---/---	---/---	---/---	---/---
12. ACLINZ	.0018/.0022	.284/.026	.027/.0009	.025/.002	.309/.026
13. AMSXXY	.0003/.0003	.001/.0003	.013/.0004	.013/.0005	.012/.0004
14. AMSXXZ	.0035/.0057	.820/.0616	.960/.028	.963/.031	1.757/.081
15. AMSYXY	.021/.138	.110/.0366	.011/.019	.030/.120	.120/.055

ERROR SOURCE NAME		EPOI ONLY PERFECT UPDATE	EPOI ONLY NO UPDATE	TLI ONLY	EPOI & TLI PERFECT UPDATE	EPOI & TLI NO UPDATE
16.	AMSYYZ	.036/.251	.190/.0368	.037/.028	.022/.279	.192/.010
17.	AMSZXZ	.028/.034	4.91/.450	1.067/.040	1.093/.059	3.934/.417
18.	AMSZYZ	.0001/.0002	.0087/.0008	.020/.0007	.019/.0007	.028/.001
19.	GDSAX	---/---	.0001/---	.020/.0007	.020/.0007	.020/.0007
20.	GDSAY	.014/.016	3.66/.216	.712/.103	.717/.098	3.148/.126
21.	GDSAZ	---/---	---/---	.013/.0004	.013/.0004	.013/.0004
22.	GCDX	.025/.169	.679/.0623	.738/.788	.740/.958	.350/.755
23.	GCDY	.016/.19	3.71/.259	6.455/.958	6/461/.952	4/270/.714
24.	GCDZ	.008/.052	.059/.0130	.628/.729	.629/.678	.636/.741
25.	GEPTX	.019/.147	.554/.464	.071/.052	.073/.199	.611/.082
26.	GEPTY	.013/.015	2.86/.207	.107/.016	.112/.018	2/776/.191
27.	GEPTZ	.006/.043	.052/.010	.006/.008	.009/.035	.053/.017
28.	ACBIAX	---/.001	.158/.012	.218/.007	.218/.007	.372/.017
29.	ACBIAY	.006/.044	.034/.0062	.010/.006	.007/.051	.036/.001
30.	ACBIAZ	.013/.016	2.36/.211	.424/.016	.411/.019	2.765/.224
31.	TIMIGU			---/---	---/---	---/---
32.	TIMCOU			3.026/.094	3.026/.094	3.026/.094

ERROR SOURCE NAME	EPOI ONLY PERFECT UPDATE	EPOI ONLY NO UPDATE	TLI ONLY	EPOI & TLI PERFECT UPDATE	EPOI & TLI NO UPDATE
33. FTD			.113/.024	.113/.024	.113/.024
34. ISPD			.024/.002	.024/.002	.024/.002
35. MASSD			.143/.025	.143/.025	.143/.025
36. MASD-1	.011/.020	.011/.020		.011/.020	.011/.020
37. MASD-2	.020/.039	.020/.039		.020/.039	.020/.039
38. MASD-3	.018/.036	.018/.036		.018/.036	.018/.036
39. FTD-1	.012/.023	.012/.023		.012/.023	.012/.023
40. FTD-2	.042/.079	.042/.079		.042/.079	.042/.079
41. FTD-3	.004/.008	.004/.008		.004/.008	.004/.008
42. ISPD-1	.011/.021	.011/.021		.011/.021	.011/.021
43. ISPD-2	---/---	---/---		---/---	---/---
44. ISPD-3	---/---	---/---		---/---	---/---

TABLE 5

ERROR SOURCES WHICH REQUIRED MORE THAN 0.5 fps (1σ)

FOR THE FIRST MIDCOURSE CORRECTION

EPOI ONLY PERFECT UPDATE	EPOI ONLY NO UPDATE	TLI ONLY	EPOI & TLI PERFECT UPDATE	EPOI & TLI NO UPDATE
	GMUX	AMSXXZ	AMSXXZ	GMUX
	INMISY	AMSZXZ	AMSZXZ	INMISY
	ASFZ	GDSAY	GDSAY	ASFZ
	AMSXXZ	GCDX	GCDX	AMSXXZ
	AMSZXZ	GDCY	GCDY	AMSZXZ
	GDSAY	GCDZ	GCDZ	GDSAY
	GCDX	TIMCOU	TIMCOU	GCDY
	GCDY			GCDZ
	GEPTX			GEPTX
	GEPTY			GEPTY
	ACBIAZ			ACBIAZ
				TIMCOU